PROTON NEEDS OF MU2E, MU2E-II, AND BEYOND (ENIGMA)

Eric Prebys, UC Davis

Booster Storage Ring (BSR) Workshop
December 15, 2020

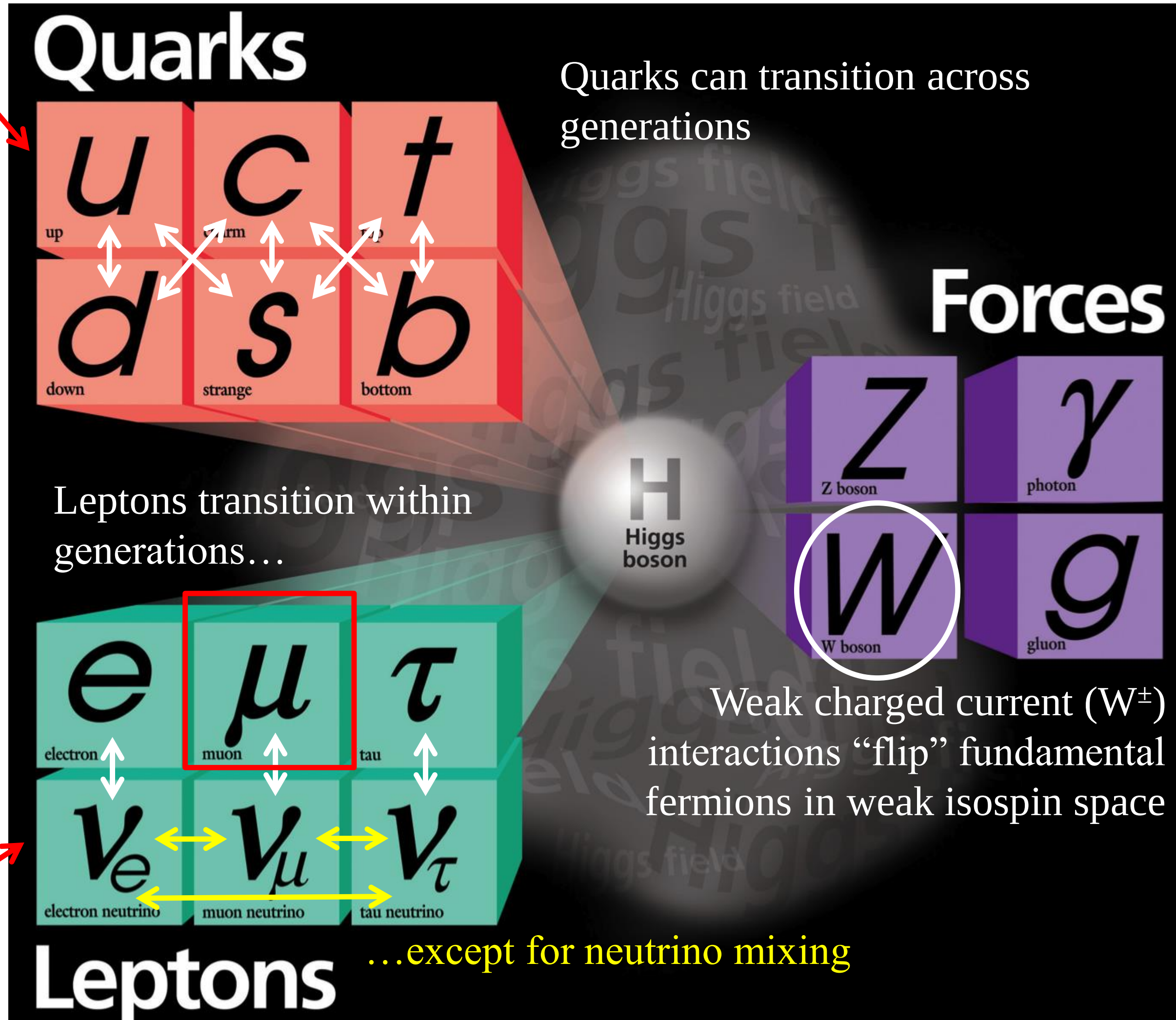
Muons in The Standard Model

Spin ½ “Fermions”

Spin 1 “Bosons”

Combine to form hadrons

Mediate interactions



Free

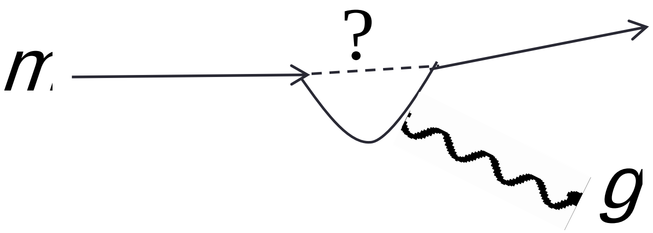
Charged Lepton Flavor Violation (CLFV)

- “Charged Lepton Flavor Violation” is the direct transition between two lepton generations.
- It is forbidden in the Standard Model*, HOWEVER
- Because extensions to the Standard Model couple the lepton and quark sectors, Charged Lepton Flavor Violation (CLFV) is a nearly universal feature of such models.
- The fact that it has not yet been observed already places strong constraints on these models.
- CLFV is a powerful probe of multi-TeV scale dynamics
  - complementary to direct collider searches
- Among various possible CLFV modes, rare muon processes offer the best combination of broad physics reach and experimental sensitivity

*except for an *extremely* tiny rate from virtual neutrino mixing.

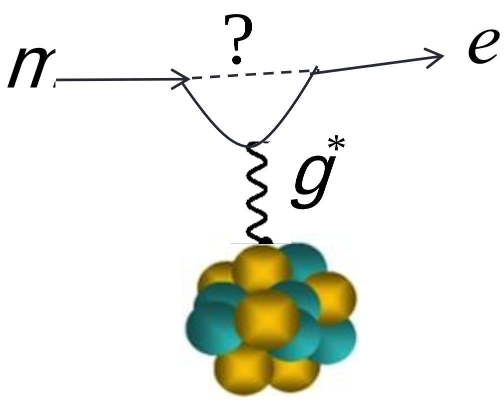
Decay vs. Conversion

- Only the “dipole”-like reactions can lead to a decay

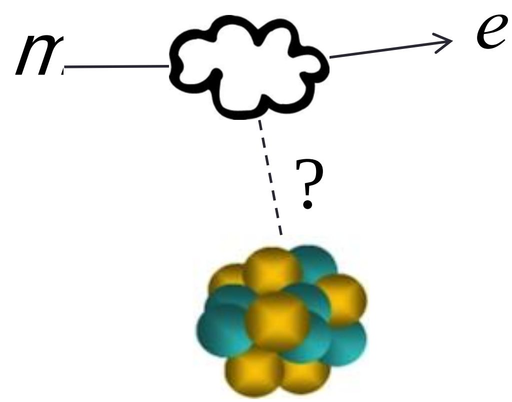


$$m \to e + g$$

- However, if we capture a μ^- on a nucleus, it could could “convert” to an e^- via exchange of a virtual particle in both scenarios

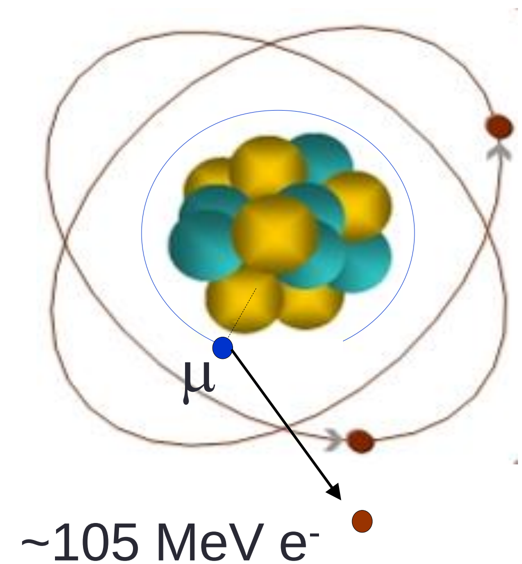


photon



heavy neutral boson

Experimental Signature of μ+N → e+N

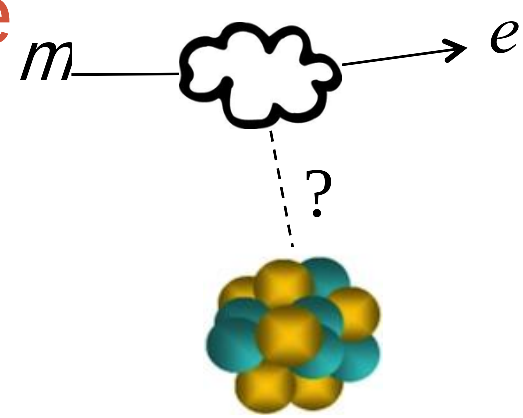


- When captured by a nucleus, a muon will have an enhanced probability of exchanging a virtual particle with the nucleus.
- This reaction recoils against the entire nucleus, producing a *mono-energetic* electron carrying most of the muon rest energy

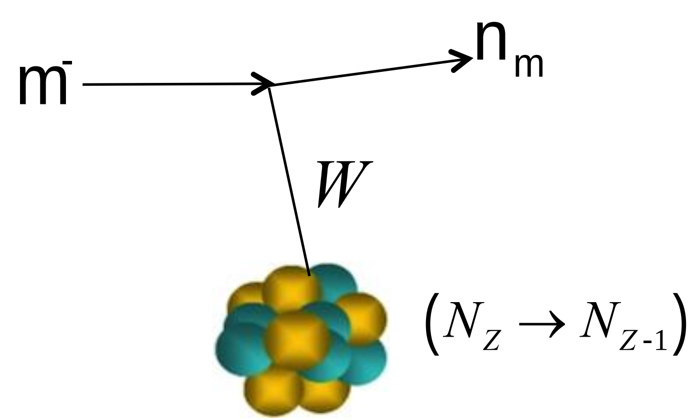
$$E_e = m_m c^2 - \frac{\left(m_e c^2\right)^2}{2 m_N c^2} \sim 105 \text{ MeV}$$

- Very clean and striking experimental signature!

What We (Plan to) Measure



- We will measure the rate of μ to *e* conversion…



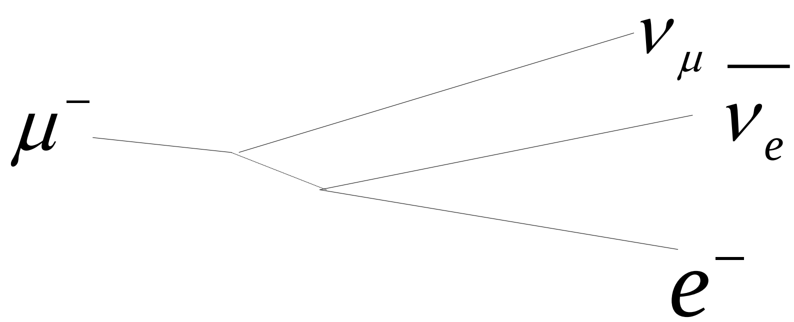
…relative to ordinary μ capture
(~2/3 of the time)

- This is defined as

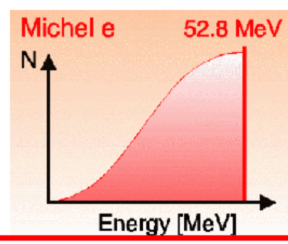
$$\boxed{R_{\mu e}} \equiv \frac{\Gamma\left(\mu^- N(A,Z) \rightarrow e^- + \mathrm{N(A,Z)}\right)}{\Gamma\left(\mu^- \mathrm{N(A,Z)} \rightarrow \nu_\mu + \mathrm{N'(A,Z\text{-}1)}\right)}$$

Biggest Issue: Decay in Orbit (DIO)

Free μ Decay:

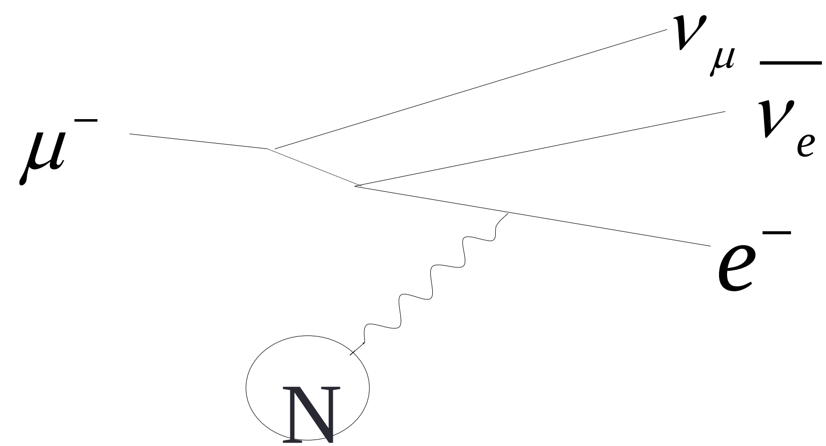


- Very high rate
- “Michel Spectrum”
  - Peak energy ~53 MeV



- Must design detector to be very *insensitive* to these.

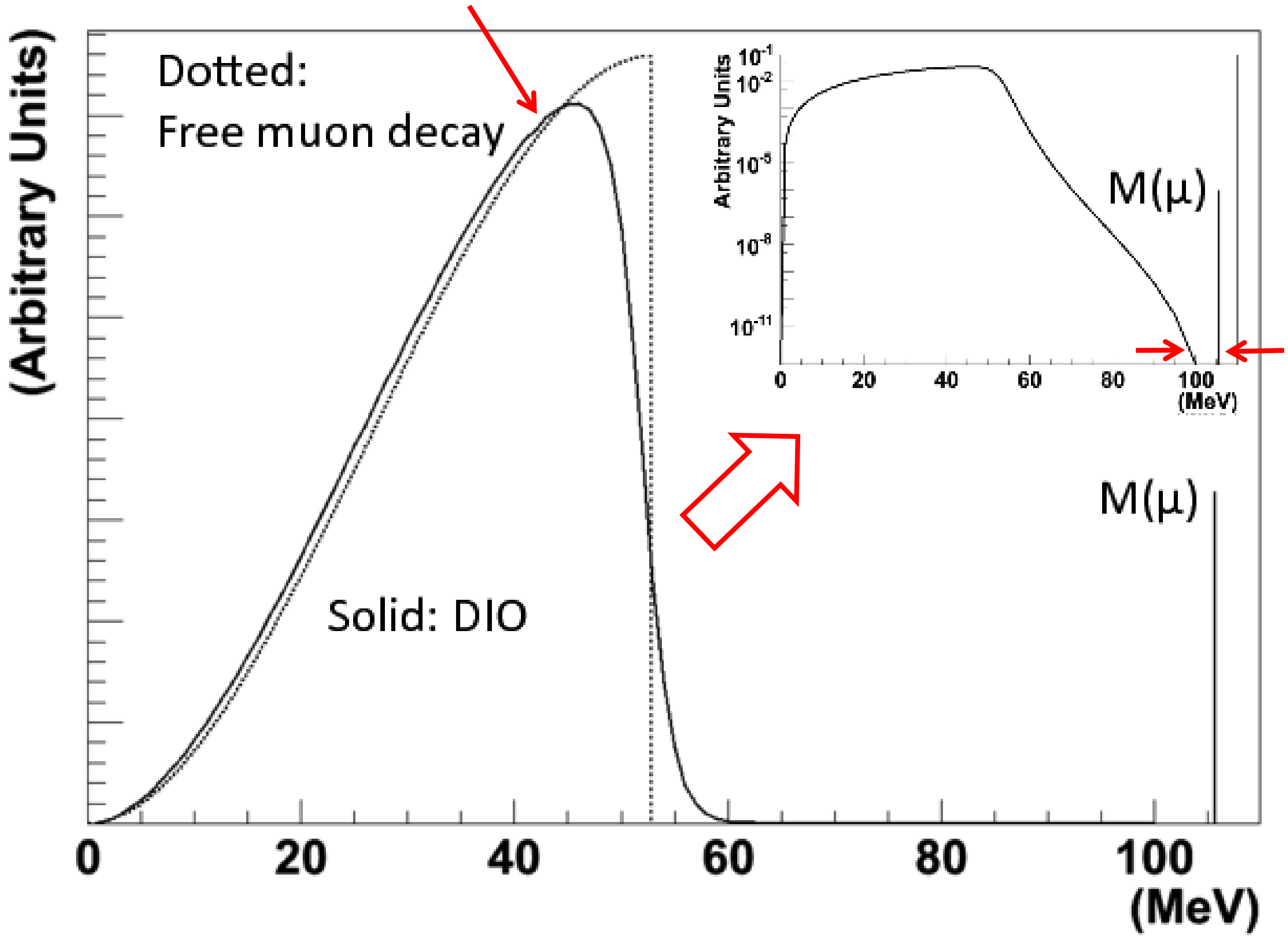
Coherent DIO:



- Nucleus coherently balances momentum and smears out Michel Spectrum.
- Rate approaches conversion (endpoint) energy as ~$(E_{conversion}-E)^5$
- Drives resolution requirement.

Decay in Orbit Spectrum

We want to be blind to this (acceptance)



We must resolve this

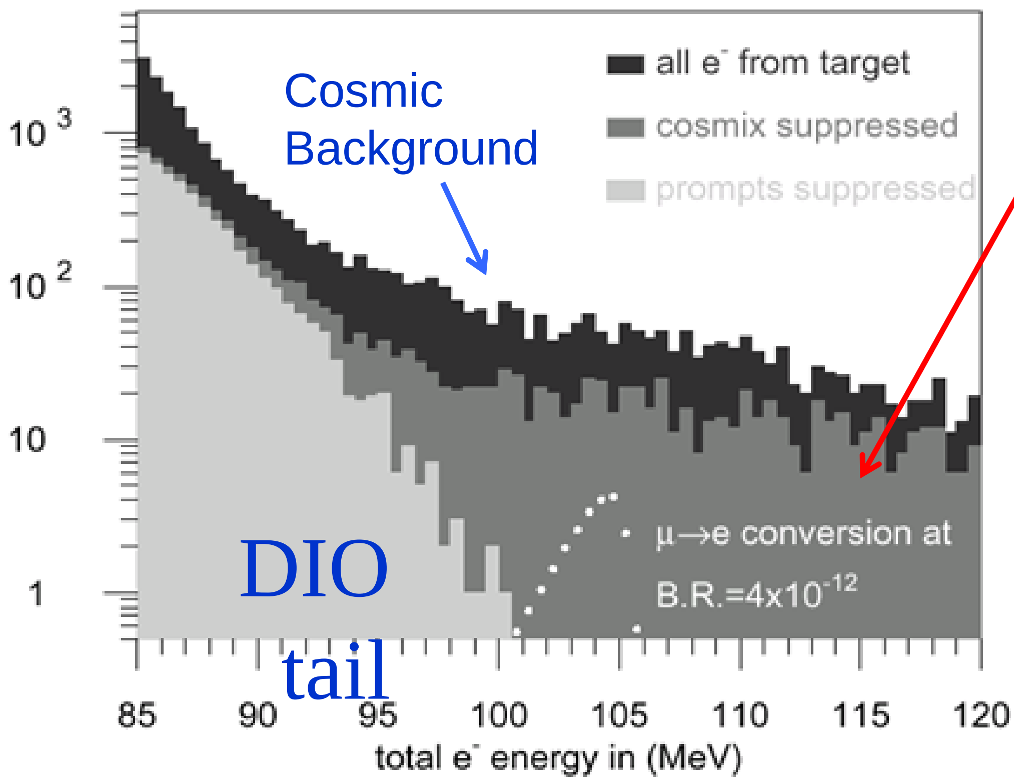
Prompt Backgrounds

- There are significant backgrounds which are “prompt” with respect to the production and capture of muons:
  - Radiative π- capture
    $\pi^- N \rightarrow N^*\gamma,\ \gamma Z \rightarrow e^+e^-$

    Biggest worry
  - Muon decay in flight
    $\mu^- \rightarrow e^-\nu\nu$
  - Pion decay in flight
    $\pi^- \rightarrow e^-\nu_e$
  - Prompt electrons
- General approach
  - Produce muons
  - Transport muons to target where some are captured.
  - Wait(!) for prompt backgrounds to go away
  - Open detection window to look for conversion of captured muons.

Experimental Challenge of "Waiting"

μ–>e Conversion: Sindrum II

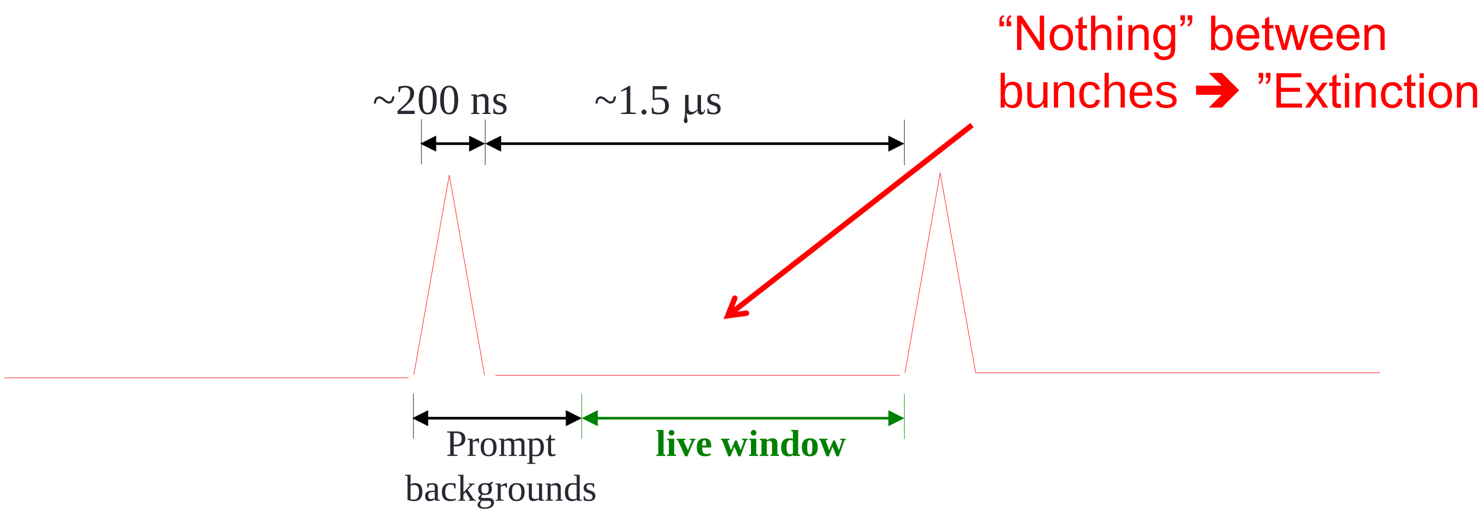


$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- Au \to e^- Au\right)}{\Gamma\left(\mu^- Au \to \text{capture}\right)} < 7\times 10^{-13}$$

- Most backgrounds are ~prompt with respect to the proton beam
  - Mostly radiative pion capture
- Previous experiments suppressed these backgrounds *by vetoing all observed electrons* for a period of time after the arrival of *each charged particle on the capture target*.
  - This leads to a fundamental to a rate limitation.

Pulsed Beams (first proposed for MELC*)

- Replace individual protons with short proton *pulses*, separated by a time on the order of a muon life time.
- Veto the time after the pulse to eliminate prompt backgrounds.



- Design a transport channel to optimize the transport of right-sign, low momentum muons from the production target to the muon capture target.
- Design a detector which is very insensitive to electrons from ordinary muon decays and has excellent tracking resolution.

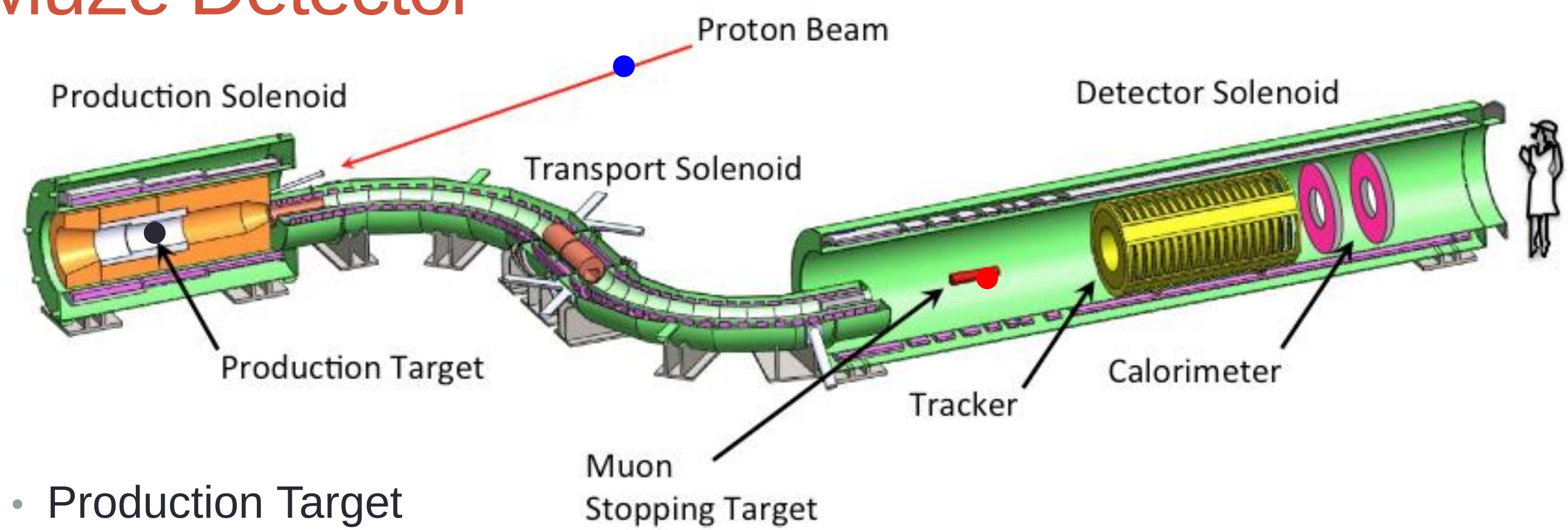
*1992, Moscow Meson Factory

Summary: Experimental Needs

- Proton beam:
  - Bunches, separated by ~muon lifetime with “nothing” in between them.
- Muon transport:
  - Optimize for low momentum, *negative* muons
- Detector:
  - Completely blind to any particle with $p \lesssim 60\ MeV/c$
  - Excellent energy resolution for $105\ MeV\ e^-$
    - →Very low mass for both target and tracker!

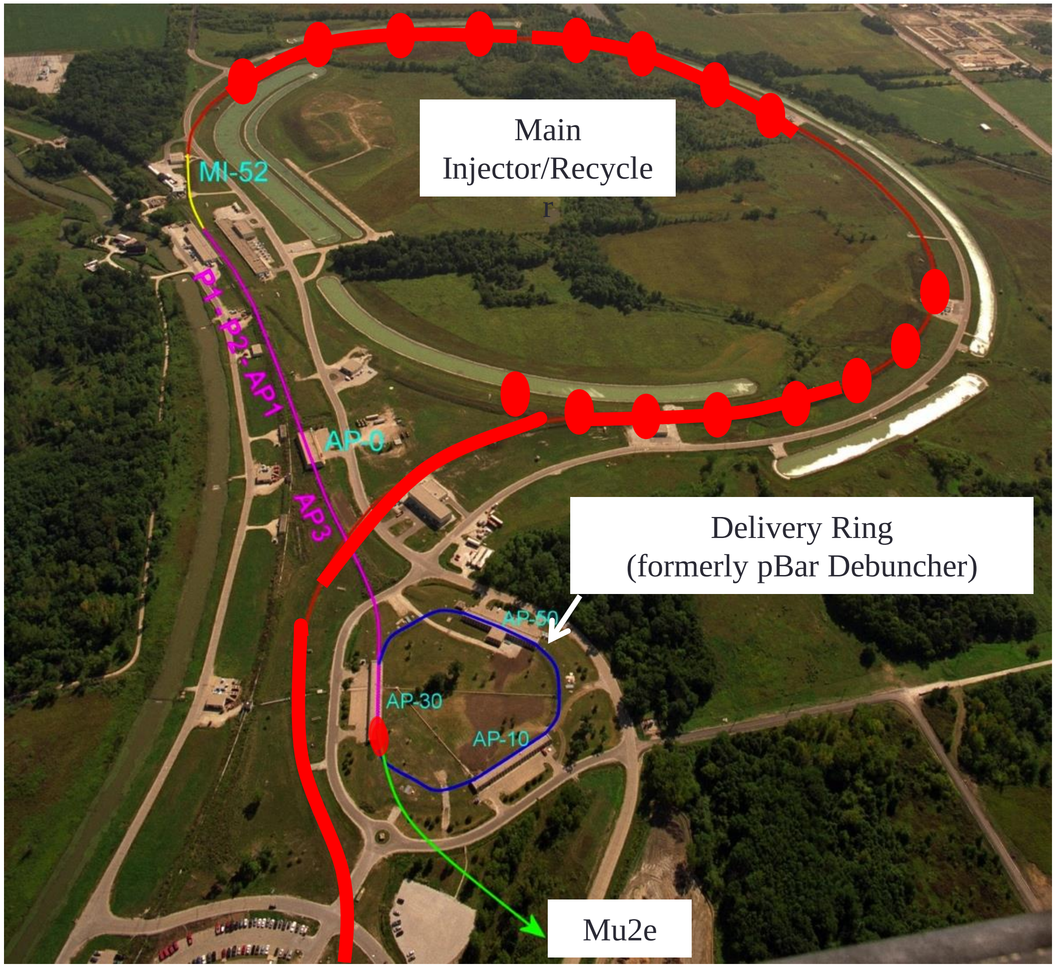
Solenoids!

Mu2e Detector



- Production Target
  - Proton beam strikes target, producing mostly pions
- Production Solenoid
  - Contains backwards pions/muons and reflects slow forward pions/muons
- Transport Solenoid
  - Selects low momentum, negative muons
- Capture Target, Detector, and Detector Solenoid
  - Capture muons on target and wait for them to decay
  - Detector blind to ordinary (Michel) decays, with $E \leq \frac{1}{2} m_\mu c^2$
  - Optimized for $E \sim m_\mu c^2$

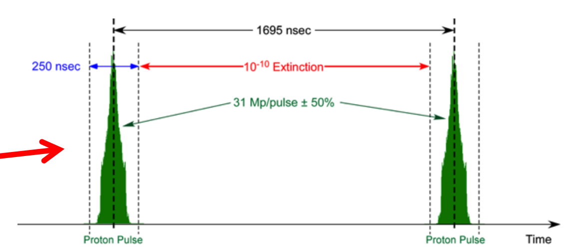
Mu2e Proton Delivery



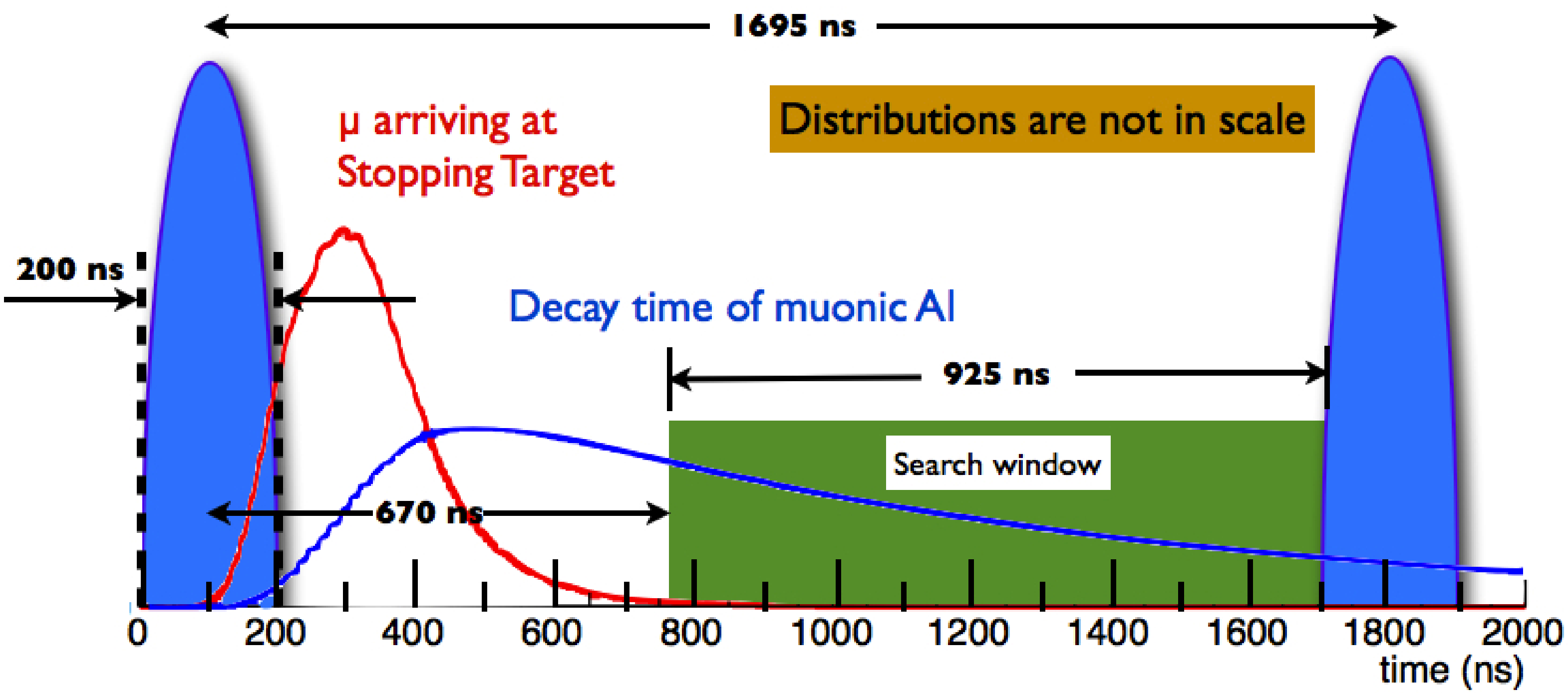
Booster

- Two Booster “batches” are injected into the Recycler (8 GeV storage ring). Each is:
  - 4×10^{12} protons
  - 1.7 μsec long
- These are divided into 8 bunches of 10^{12} each
- The bunches are extracted one at a time to the Delivery Ring
  - Period = 1.7 μsec
- As the bunch circulates, it is resonantly extracted to produce the desired beam structure.
  - Bunches of ~3×10^7 protons each
  - Separated by 1.7 μsec

Exactly what we need



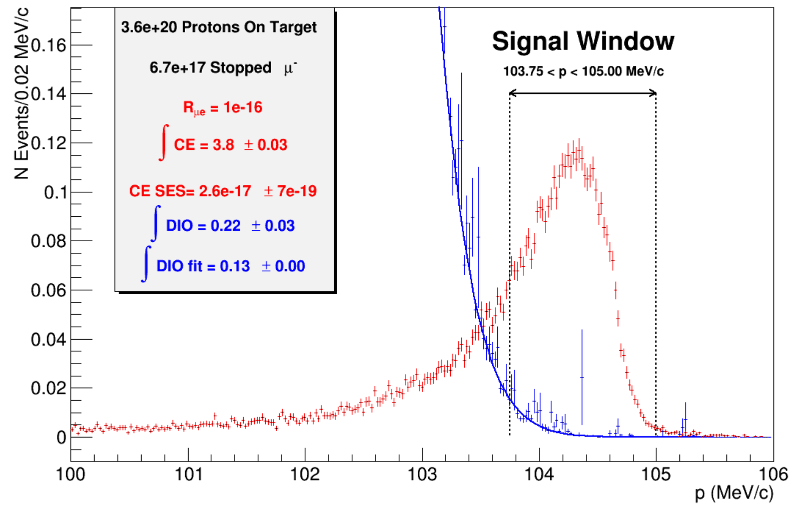
End Product



Target data set: ~3.6×10^{20} protons in ~3 years

Sensitivity

- Full Simulation (GEANT4)
- 3.6x10^{20} protons on target
  - 3 years nominal running
- Cuts chosen to maximize sensitivity



Parameter	Value
Physics run time @ 2×10^7 s/yr.	3 years
Protons on target per year	1.2×10^{20}
μ^- stops in stopping target per proton on target	0.0019
μ^- capture probability	0.609
Total acceptance x efficiency	$\left(8.5 \pm^{1.1}_{0.9}\right)\%$
Single-event sensitivity with Current Algorithms	$\left(2.87 \pm^{0.32}_{0.27}\right) \times 10^{-17}$

Single Event Sensitivity: $R_{\mu e}$=2.9x10^{-17}=Factor of 10,000 improvement over SINDRUM-II!

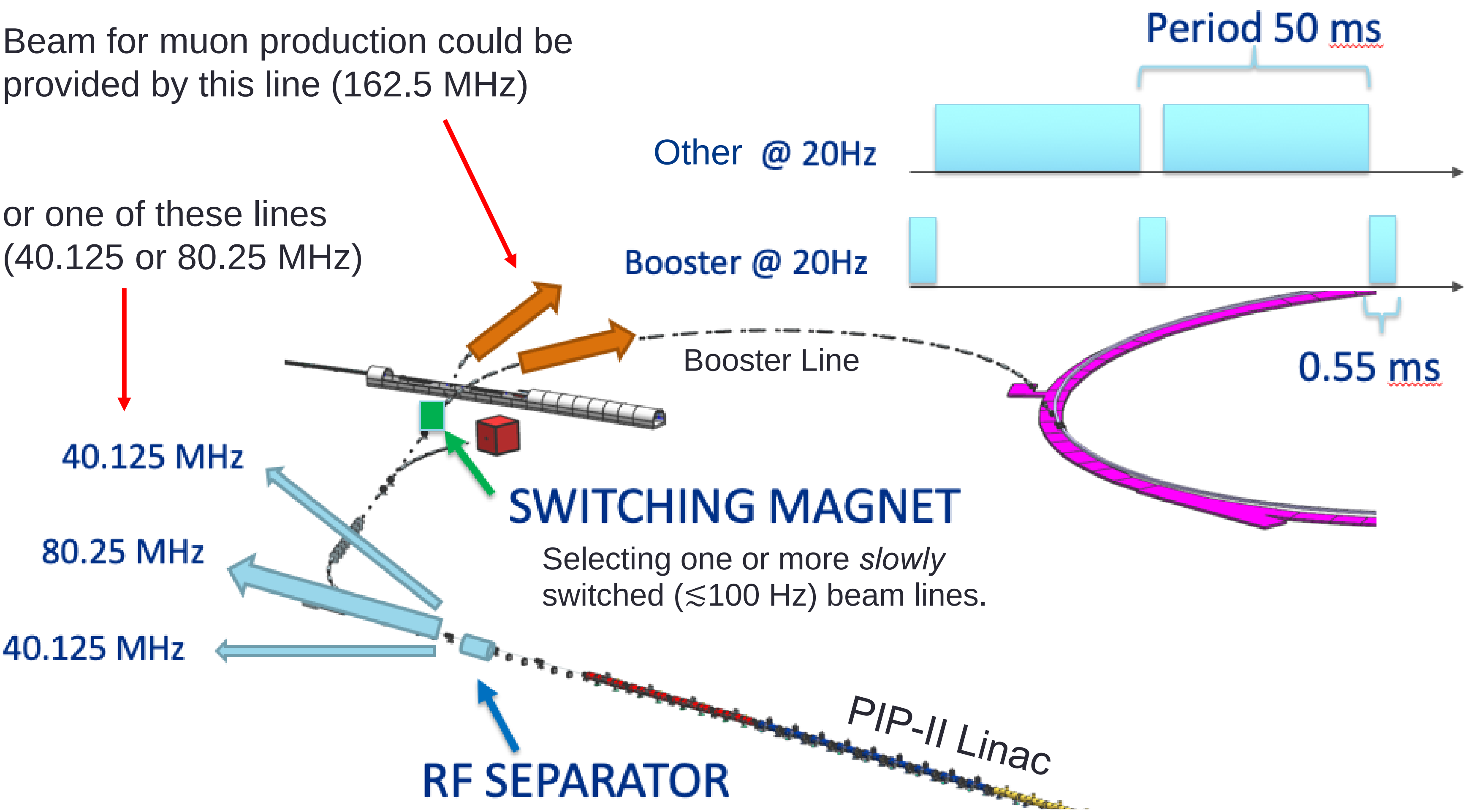
Going Beyond: PIP-II and Mu2e

- The muon production rate for 800 MeV beam is only slightly lower than that of an 8 GeV beam of the same power.
- 800 MeV is below the antiproton production threshold, which eliminates a significant background.
- Targeting the 800 MeV will require significant modification or replacement of the production solenoid and target system, which will be very radioactive by then.
  - But I’m not going to talk about this.

Beam Switching*

Beam for muon production could be provided by this line (162.5 MHz)

or one of these lines (40.125 or 80.25 MHz)

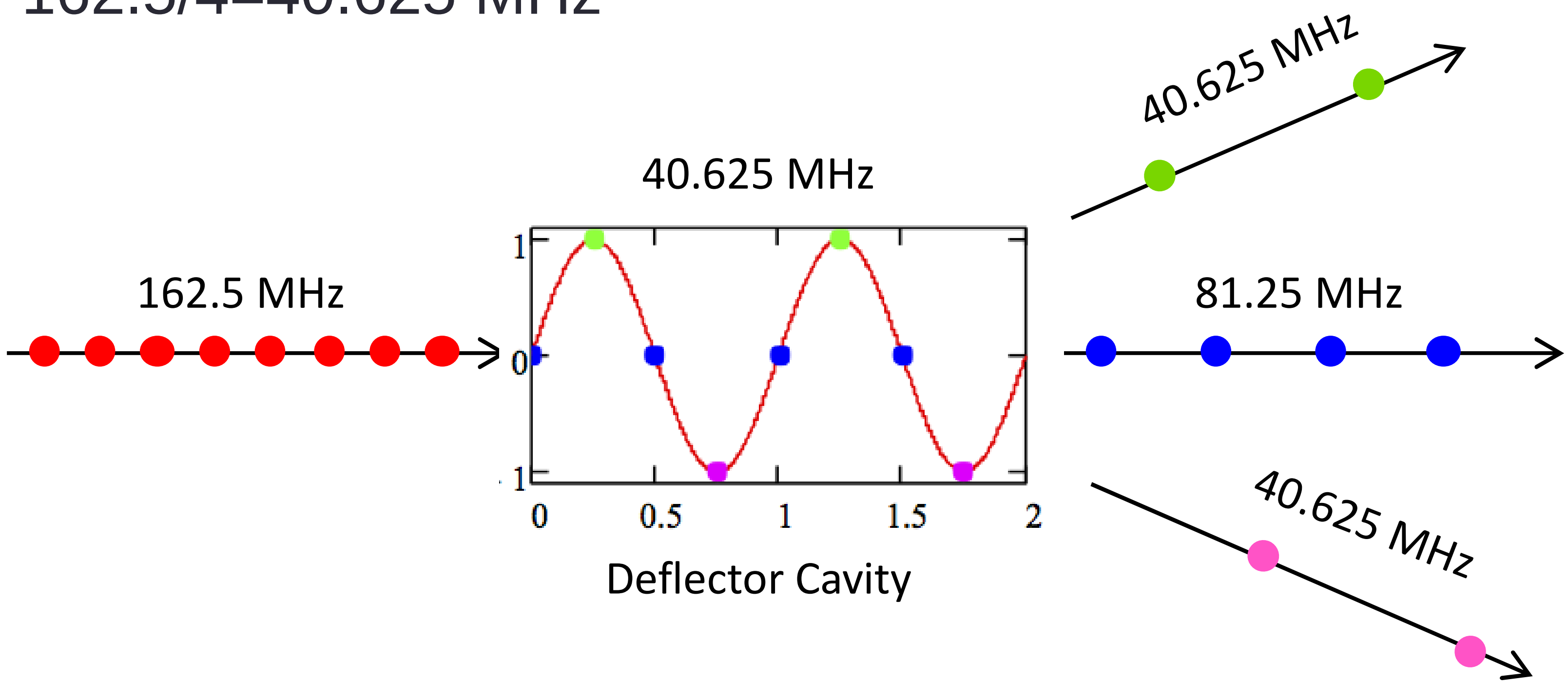


Selecting one or more *slowly* switched (≲100 Hz) beam lines.

*Lia Merminga, CD-2 Refresh

RF Beam Splitting

- The Beam will go through an RF deflector running at 162.5/4=40.625 MHz



- Individual beam lines are selected by choosing which bunches to populate.

PIP-II Linac Beam Parameters

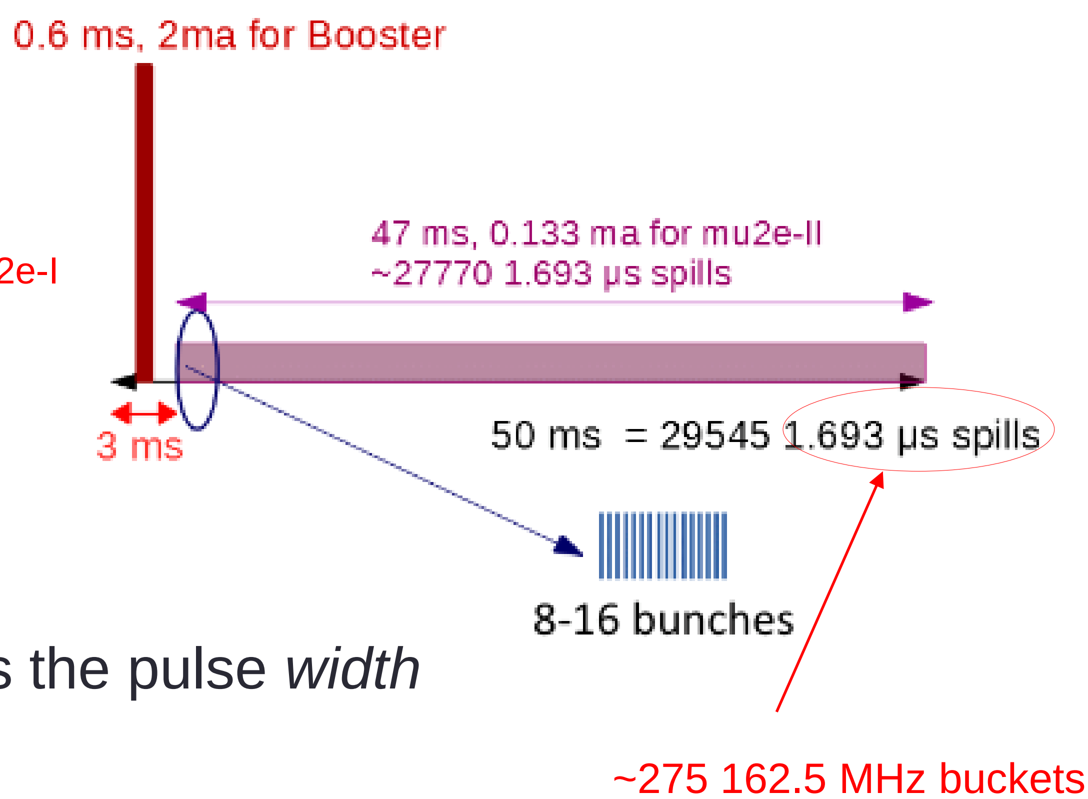
Parameter	Linac Output	Central Line	Side Lines	Comment
Energy [MeV]	800			
Bunch Length [ps]	4			
ϵ_L [ns-keV,RMS]	1.1			
σ_E [keV]	275			ϵ_L/σ_t
Max. Ave. Bunch Size	0.8×10^8			2 mA
Peak Bunch Size	$\boxed{2.0 \times 10^8}$			5 mA
Bunch Frequency [MHz]	162.5	81.25	40.625	Maximum
Bunch Separation [ns]	6.2	12.3	24.6	Minimum

Assume this limit for short bursts.
Define as n_P

Mu2e-II Beam formation*

- Possible beam structure (100 kW):
  - 8 bunch burst @ 600 kHz
  - 2.0x10^8 protons/bunch
  - 600 kHz repetition rate
  - = 118 kW
    - 3% duty factor
    - 0.15 mA

  ~10 times Mu2e-I
  - These numbers are independent from the instantaneous bunch rate!
    - ie, which line we're in
- The bunch rate only affects the pulse *width*
  - 162.5 MHz = 50 ns
  - 81.25 MHz = 100 ns
  - 40.625 MHz = 200 ns
- All of these numbers would double for 200 kW

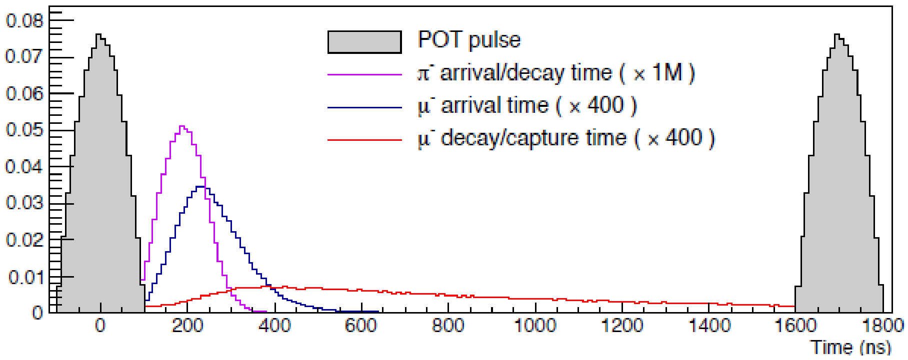


https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys-204.pdf

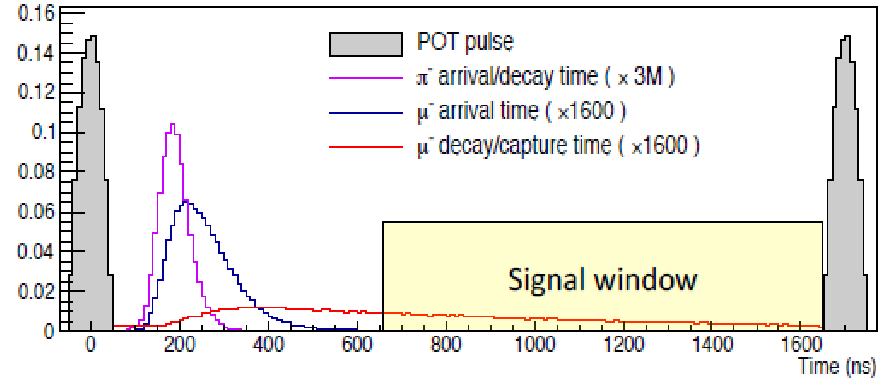
mu2e→mu2e-II

- Reducing the pulse with can extend the live window *somewhat*

Mu2e (200 ns)



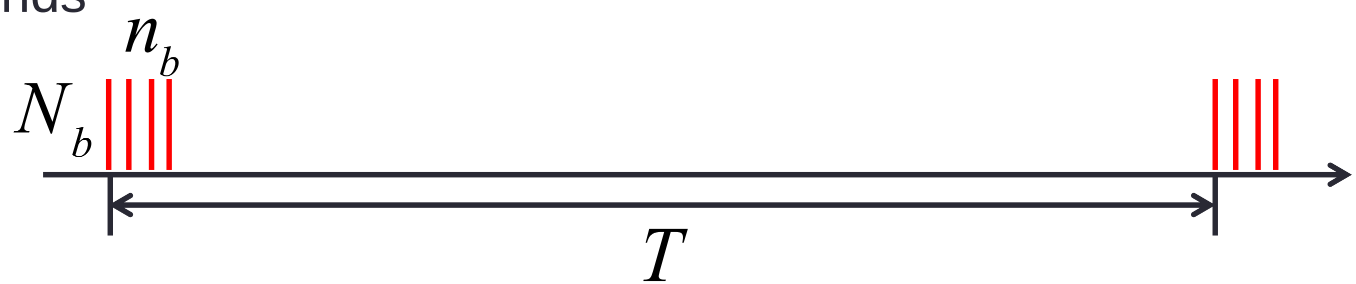
Mu2e-II (100 ns)



- However, because the distribution of the time of arrival of the muons is dominated by straggling, there is no real benefit in going to shorter pulses.

General: Calculating Beam Rate and Power

- Assume we have n_b bunches with N protons in each bunch every T seconds



$$\text{Rate [/s]} = \frac{n_b N_b}{T\ \text{[s]}}$$

$$\text{Current [mA]} = \left(\frac{N_b}{0.4\times10^8}\right)\left(\frac{n_b}{\left(T/6.2\text{ns}\right)}\right)$$

$$\text{Power [kW]} = 800\times\left(\text{Current [mA]}\right)$$

- Reminder: Limits
  - $N_{b,max}$: 2×10^8 (5 mA peak)
  - Max. I_{ave}: 2 mA

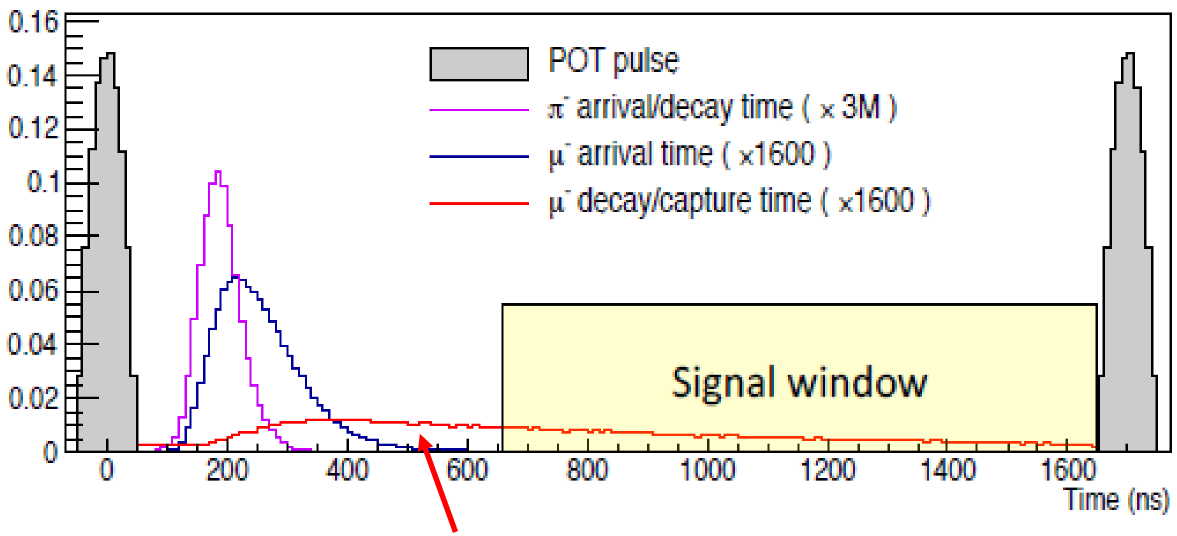
0.8x10⁸ → written as:

0.8×10^8 @ 162.5 MHz = 1.6MW
1.6×10^8 @ 81.25 MHz = 1.6MW
2.0×10^8 @ 40.625 MHz = 1.0MW
2.0×10^8 @ 20.312 MHz = 0.5MW

This will be very important

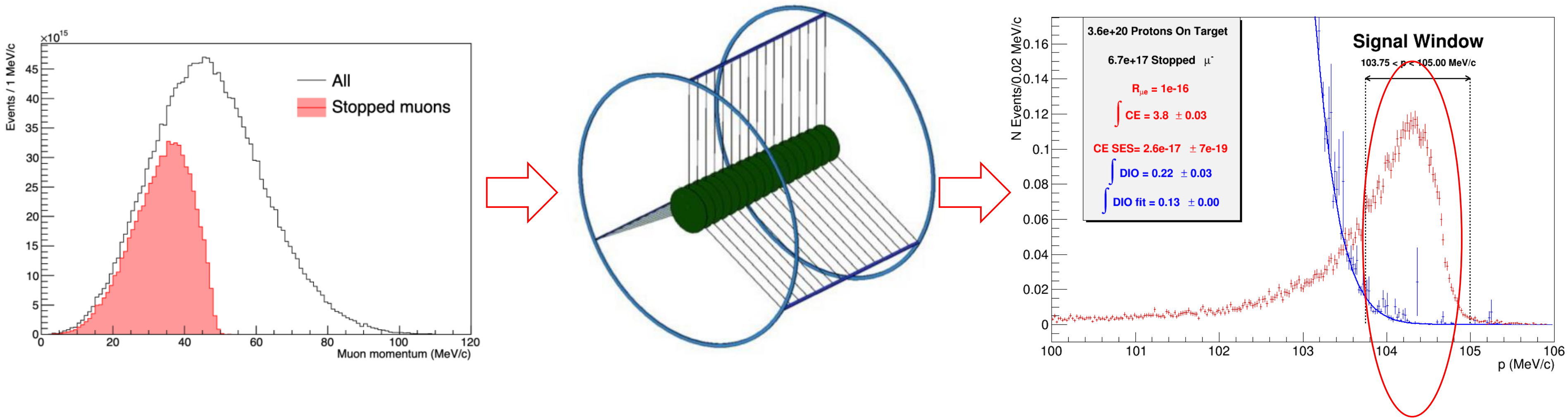
Issues Going Beyond Mu2e-II

- Issue 1:
  - We would like to go to higher Z nuclei either to enhance the rate if we don't see a signal or to study the A-dependence if we do, HOWEVER, heavier nuclei *dramatically shorten* the lifetime of the bound muons, which runs into problems with the long beam straggling time
    - Example: The probability of interaction for a gold nucleus would be enhanced by ~50, but the lifetime is only 73 ns!



This curve would be shortened so all the muons would decay away before the live window

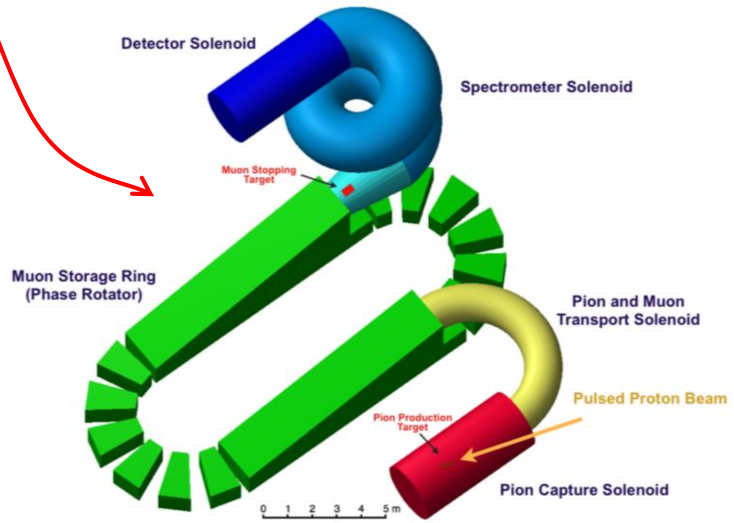
- Issue 2:
  - Our tracking resolution is limited by scattering in our multi-layer capture target, which we need because of the muon energy distribution

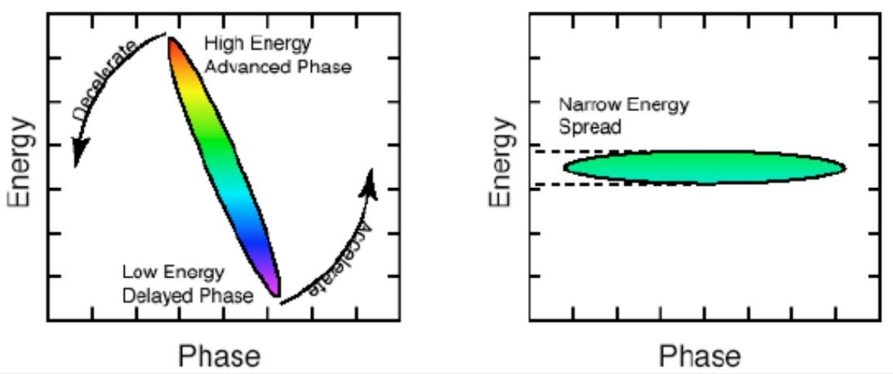


- To solve these problems, we need:
  - A different way for prompt backgrounds to die away
    - i.e. eliminate need for veto
  - A source of muons with much narrower energy distributions.

Solutions: FFA*

- This solution has been been developed for next generation of the competing COMET experiment at J-Parc
- Muons will be injected into an FFA for about ~6 turns
  - All the pions will decay away (eliminating the need for the veto)
  - The beam will be phase rotated to reduce the energy spread.





- Ultimately want 500-1000 kW!

*J. Pasternak, "PRISM - an FFA for high intensity muon beam", CLFV Workshop, 12/10/2020

Need for a Bunch Compressor

- In order to work, an FFA would need
  - > 10^{12} protons
  - < 30 ns
  - 100-1000 Hz
- $10^{12} = 5000\text{x}(2\text{x}10^{8}) = 31\ \mu\text{sec}$

1000 times too long!

  - For these experiments, we need some sort of “bunch compressor” to accumulate beam into larger bunches, and then extract them to experiments.
- Two LoIs were submitted related to this:
  - E. Prebys, *et al*, “Letter of Interest: Bunch Compressor for the PIP-II Linac”,(Green field, permanent magnet ring) https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys2-203.pdf
  - W. Pellico, *et al*, “FNAL Booster Storage Ring”,(this workshop) https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0_pellico-029.pdf

Ring Size and Space Charge Considerations

- Once we've fixed the injection energy, the space charge tune shift limit is given by

Bunch size

Number of bunches

~limit

Bunch length

Peak Current/Average Current

$$|\Delta \nu| = \frac{B n_b N_b r_0}{4\pi\beta\gamma^2 \epsilon_N} \lessapprox .2 \rightarrow N_{b,\max} \propto \frac{\epsilon_N}{B n_b} = \boxed{\frac{t_b}{\tau}\epsilon_N}$$

Normalized emittance

period

- Maximize t_b → longitudinal painting
- Minimize τ put a pin in that
- Maximize ϵ_N → transverse painting
  - No longer limited by MI aperture, but not without consequences

Comparing Small Ring to BSR

- Assume f_{ext} = 100Hz, Δ_ν=.2

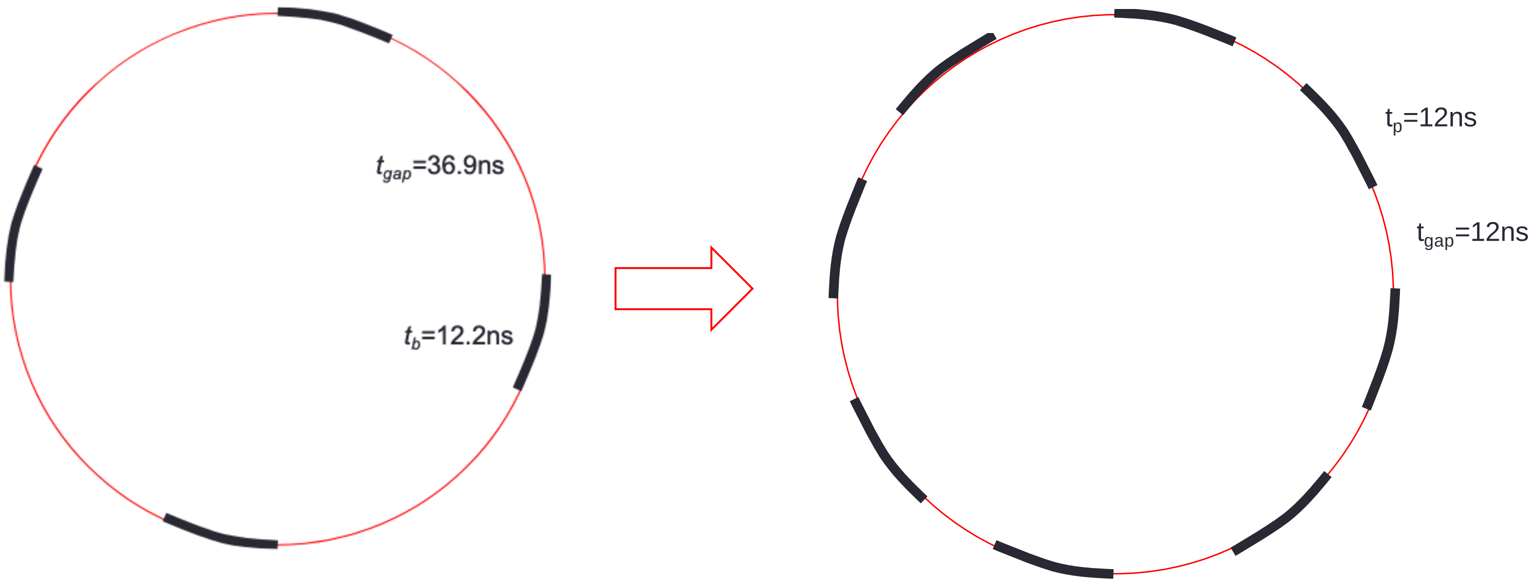
	C=50 m			C=500 m (BSR)		
Power [kW]	100	500	1000	100	500	1000
N_b $[10^{12}]$	7.8	39.1	78.1	7.8	39.1	78.1
ϵ_N [π-mm-mr]	27	134	267	267	1340	2670

>>SNS

- But can we even get to 1MW?
  - At 20.31 MHz, power is limited to 500 kW by the $2\text{x}10^8$ bunch size

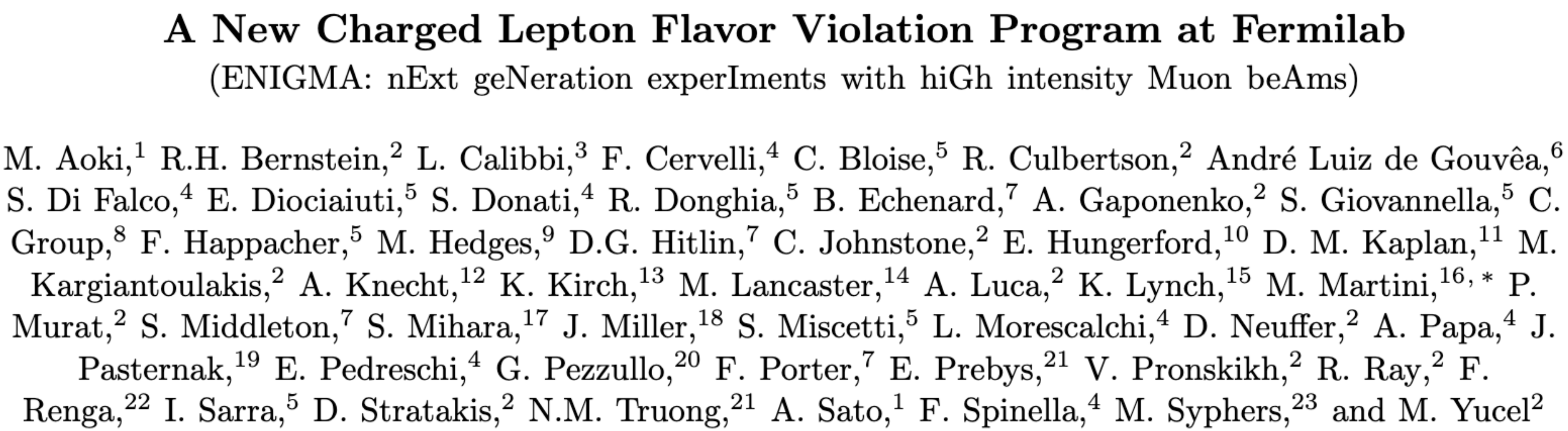
Going from 500 kW to 1 MW

- Must go from 20.31 MHz to 40.625 MHz



- Now need a 100 Hz kicker with a < 10 ns full rise and fall time
  - This is very hard
- Might be easier to go to two rings?

Overall Needs of Next Generatio Muon Program*


A New Charged Lepton Flavor Violation Program at Fermilab
(ENIGMA: nExt geNeration experIments with hiGh intensity Muon beAms)

M. Aoki,[1] R.H. Bernstein,[2] L. Calibbi,[3] F. Cervelli,[4] C. Bloise,[5] R. Culbertson,[2] André Luiz de Gouvêa,[6] S. Di Falco,[4] E. Diociaiuti,[5] S. Donati,[4] R. Donghia,[5] B. Echenard,[7] A. Gaponenko,[2] S. Giovannella,[5] C. Group,[8] F. Happacher,[5] M. Hedges,[9] D.G. Hitlin,[7] C. Johnstone,[2] E. Hungerford,[10] D. M. Kaplan,[11] M. Kargiantoulakis,[2] A. Knecht,[12] K. Kirch,[13] M. Lancaster,[14] A. Luca,[2] K. Lynch,[15] M. Martini,[16,*] P. Murat,[2] S. Middleton,[7] S. Mihara,[17] J. Miller,[18] S. Miscetti,[5] L. Morescalchi,[4] D. Neuffer,[2] A. Papa,[4] J. Pasternak,[19] E. Pedreschi,[4] G. Pezzullo,[20] F. Porter,[7] E. Prebys,[21] V. Pronskikh,[2] R. Ray,[2] F. Renga,[22] I. Sarra,[5] D. Stratakis,[2] N.M. Truong,[21] A. Sato,[1] F. Spinella,[4] M. Syphers,[23] and M. Yucel[2]

- https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF5_RF0-AF5_AF0_Robert_Bernstein-027.pdf

BACKUP

Generation (Flavor) Transitions

- In both the quark and lepton sector, the weak eigenstates are related to the mass eigenstates by a unitary matrix

$$\begin{bmatrix} d' & s' & b' \end{bmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

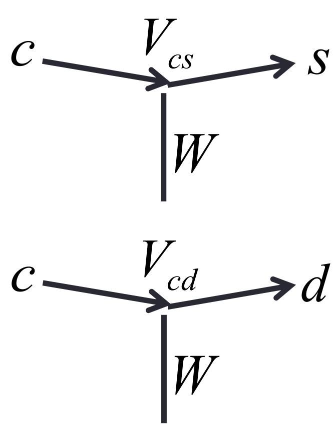
"almost" diagonal

$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

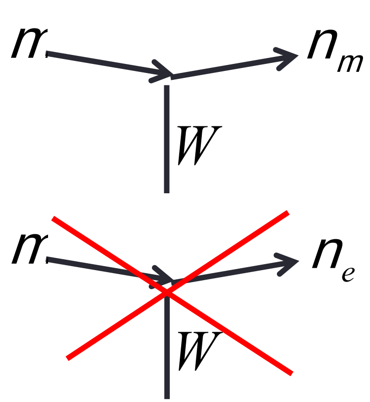
~maximum mixing

- However, because the neutrino masses and their differences are so small, the phenomenology is *very* different

Quarks: generational transitions observed



Leptons: weak transitions and mixing proceed separately



Pure weak state. Propagates as a superposition of mass eigenstates→"neutrino mixing"

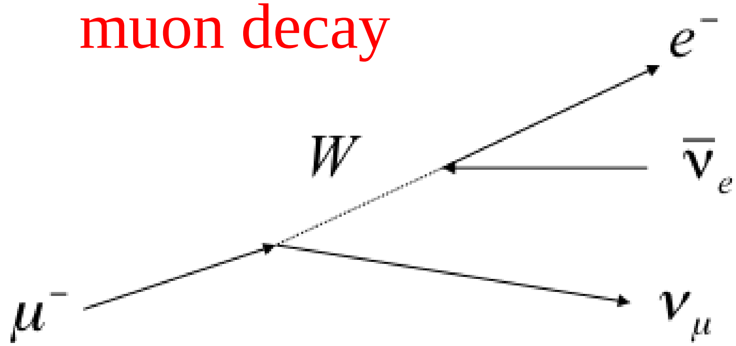
NOT observed!

Lepton Number and Lepton Flavor Number

As a consequence, both lepton number and lepton "flavor" (generation) number are individually conserved*

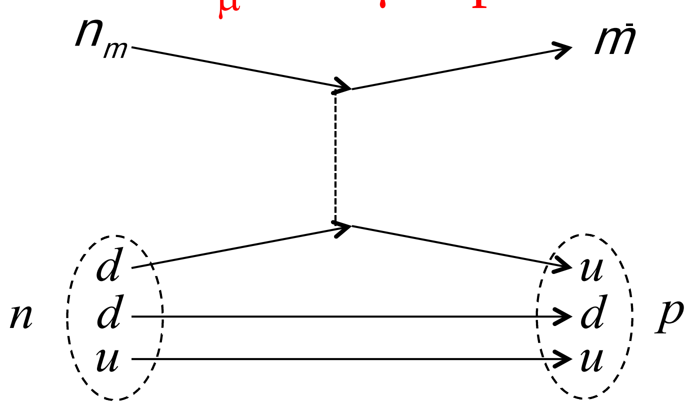
	l	l_e	l_m
m^-	1	0	1
total	1	0	1

muon decay



	l	l_e	l_m
e^-	1	1	0
$\bar{n}_e$	-1	-1	0
n_m	1	0	1
total	1	0	1

$\nu_\mu + n \rightarrow \mu^- + p$



	l	l_e	l_m
n_m	1	0	1
n	0	0	0
total	1	0	1

	l	l_e	l_m
m^-	1	0	1
p	0	0	0
total	1	0	1

*except in neutrino mixing

Choosing the Capture Target

- The probability of of exchanging a virtual particle with the nucleus goes up with Z, *however*
- Lifetime is *shorter* for high-Z
  - Decreases useful live window
- Also, need to avoid background from radiative muon capture limits choices

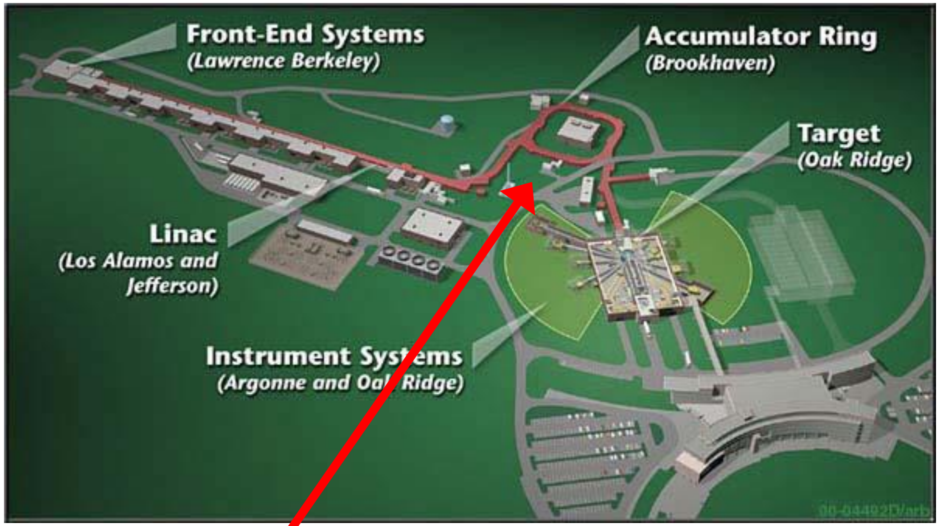
$$\mu N \to \nu_\mu N'\gamma$$
$$\hookrightarrow e^+ e^-$$

$\Rightarrow$Want M(Z)-M(Z-1) < signal energy

$\Rightarrow$Aluminum is initial choice for Mu2e

Nucleus	$R_{\mu e}(Z)$ / $R_{\mu e}(Al)$	Bound lifetime	Atomic Bind. Energy(1s)	Conversion Electron Energy	Prob decay >700 ns
Al(13,27)	1.0	.88 μs	0.47 MeV	104.97 MeV	0.45
Ti(22,~48)	1.7	.328 μs	1.36 MeV	104.18 MeV	0.16
Au(79,~197)	~0.8-1.5	.0726 μs	10.08 MeV	95.56 MeV	negligible

Example: Spallation Neutron Source Example



- The SNS accumulator ring has the following parameters
  - K = 1 GeV
  - C = 220 m (50 m is probably unrealistic)
  - Power = 1.3 MW
  - Normalized emittance = $\boxed{220\ \pi\text{-mm-mr}}$
  - Extraction rate = $\boxed{60\ \text{Hz}}$
    - BUT with a 200 ns rise time, while we need ~20ns rise AND fall times!
- This gives us an idea of the scale of the problem…